

LOOKING DEEP INTO THE CAT’S EYE: STRUCTURE AND ROTATION IN THE FAST WIND OF THE PN CENTRAL STAR OF NGC 6543

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ABSTRACT

We present *HST*/STIS time-series spectroscopy of the central star of the ‘Cat’s Eye’ planetary nebula NGC 6543. Intensive monitoring of the UV lines over a 5.8 hour period reveals well defined details of large-scale structure in the fast wind, which are exploited to provide new constraints on the rotation rate of the central star. We derive characteristics of the line profile variability that support a physical origin due to co-rotating interaction regions (CIRs) that are rooted at the stellar surface. The recurrence time of the observed spectral signatures of the CIRs is used to estimate the rotation period of the central star and, adopting a radius between 0.3 and 0.6 R_{\odot} constrains the rotational velocity to the range $54 \leq v_{\text{rot}} \leq 108 \text{ km s}^{-1}$. The implications of these results for single star evolution are discussed based on models calculated here for low-mass stars. Our models predict a sub-surface convective layer in NGC 6543 which we argue to be causally connected to the occurrence of structure in the fast wind.

Subject headings: stars: winds, outflows — stars: evolution — ultraviolet: stars

1. INTRODUCTION

Planetary nebulae (PNe) display remarkably diverse morphologies, the large majority of which are not spherical. The formation and shaping of bipolar PNe, which can include axial and point-symmetries, is currently a moot issue in stellar astrophysics, with the likelihood that different mechanisms may be more dominant in different nebulae. An understanding of this PNe diversity encompasses the potential roles of several interesting physical processes, including magnetic fields, common envelope evolution in binary systems, stellar radiation fields and outflows.

One of contending scenarios for sculpting the nebulae is based on stellar rotation in the Generalized Interacting Stellar Wind model (GISW e.g., Frank 1999). In this case, asymmetry results from an equatorially enhanced outflow from a post-asymptotic giant branch (AGB). The higher equatorial density constrains the nebular expansion in that region, leading to an elliptical or bipolar PN. The origin of the requisite equatorial expansion remains uncertain, but rotationally induced aspherical mass-loss from the central star is one of the favoured scenarios (e.g., Dwarkadas & Owocki 2002; García-Segura et al. 2005). In a radiatively driven wind, rotation may result in latitudinal variations in the wind, with high velocities and larger wind-momentum gas at the poles compared to the equator. Rotation can also significantly affect the magnetic channelling of a hot star wind (e.g., Ud-Doula et al. 2008).

A pivotal issue in the role of stellar rotation in PNe – and the subject of this Letter – is whether the precursor (AGB) and remnant (CSPN) rotation is fast enough to produce the contrasting equatorial and polar outflows. Observational constraints on AGB rotation rates suggest upper limits of a few km s^{-1} (e.g., de Medeiros & Mayor 1999), though Ignace et al. (1996) argue that very modest rotation rates in AGB stars are not likely to result in aspherical geometries. In their study of the evolution of rotating stars from main-sequence to white dwarf, Suijs et al. (2008) predict that single star progenitors of CSPNe have very little or no rotation at all

in this phase.

In this Letter we provide new perspectives and constraints on the rotation of CSPN by studying the temporal evolution of large-scale (coherent) wind structure, which we argue is rooted at the stellar surface. Over the past two decades extensive UV spectral time-series observations of OB and WR stars, obtained primarily with the *International Ultraviolet Explorer* (IUE) satellite, have revealed systematic behaviour of wind variability. The most thoroughly studied objects exhibit cyclical variation in the stellar winds that are causally connected to the photosphere, with the time-scales of the variability related to the rotation periods of the massive stars (e.g., Massa et al. 1995; Fullerton et al. 1996; Kaper et al. 1996; de Jong et al. 2001; Prinja et al. 2002; Chené & St-Louis 2011). The physical interpretation of this rotational modulation is the action of spiral-shaped structure in the wind flow caused by perturbations at the base of the wind and carried by stellar rotation. Using *Far-Ultraviolet Spectroscopic Explorer* (FUSE) data, similar wind structure has been demonstrated to exist in the fast winds of CSPN (e.g., Prinja et al. 2007, 2012).

In this Letter we report on high-resolution, high-quality *Hubble Space Telescope* (*HST*) time-series spectroscopy of the central star of the hydrogen-rich (Cat’s Eye) nebula NGC 6543. The time dependence of the fast wind of NGC 6543 was previously shown to exhibit discrete absorption components, which traverse the absorption troughs of unsaturated wind lines on time-scales $\lesssim 1$ hour (Prinja et al. 2007). We present here a multi-line study of the variability in the *HST* spectra. The clarity of the structure seen in the resonance, excited state and iron UV lines provides key details on the nature of the wind structure, and thus its origins and connection to the rotation of the central star.

2. *HST*/STIS OBSERVATIONS

The central star (HD 164963) of the well studied PN NGC 6543 was observed with *HST* for Program #12489 (D. Massa PI) on 2012 May 16. Repeated Space Telescope Imag-

TABLE 1
ADOPTED PARAMETERS FOR THE CENTRAL STAR OF NGC 6543

Parameter	Value
Spectral type	Of(H-rich)
Luminosity	$1585L_{\odot}$
T_{eff}	67000 K
Radius	$0.3R_{\odot}$
Radial velocity	-66 km s^{-1}
Terminal velocity	1340 km s^{-1}
Velocity law (β)	2

NOTE. — Parameters are from the non-LTE analysis of Georgiev et al. 2008

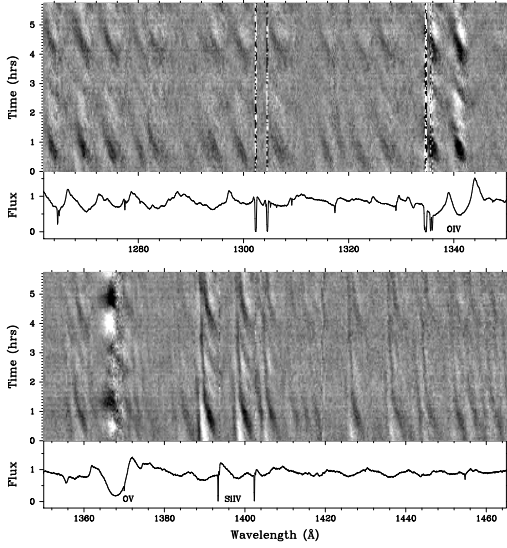


FIG. 1.— Dynamic spectra revealing evidence for systematic variability in almost every detectable absorption line in the *HST*/STIS spectrum of the central star of NGC 6543. Recurrent large-scale wind structure is diagnosed by the SiIV resonance doublet and OIV and OV excited state lines. Sympathetic variations are also evident in numerous FeVI ($\lambda\lambda 1260$ to 1310) and FeV ($\lambda\lambda 1390$ to 1460) lines.

ing Spectrograph (STIS) E140M grating (spectral resolution $\simeq 10 \text{ km s}^{-1}$) observations were secured for 5 contiguous *HST* orbits in ACCUM mode and with individual exposure times of 180-s. A total time-series of 95 spectra were secured spanning ~ 5.8 hours, each with a wavelength range $\sim \lambda\lambda 1140$ to 1710 \AA . The signal-to-noise resolution per element of an individual spectrum varies from ~ 5 at the extreme wavelength ends to ~ 30 at 1300 \AA .

The rich UV spectrum of HD 164963 contains several key diagnostic lines including the resonance line doublets of NV $\lambda\lambda 1239, 1243$, SiIV $\lambda\lambda 1394, 1403$, and CIV $\lambda\lambda 1549, 1551$; the excited state wind lines of OIV $\lambda\lambda 1339, 1344$ and OV $\lambda 1371$; HeII $\lambda 1640$, as well as ‘forests’ of FeV and FeVI absorption lines. Table 1 lists the fundamental parameters of HD 164963 we adopt for this paper.

3. EVIDENCE FOR EVOLVING LARGE-SCALE WIND STRUCTURE

Previous studies established that the fast wind of NGC 6543 is variable on short (\sim hourly) time-scales, with diagnostic changes evident in optical spectroscopy (Mendez et al. 1990), photometry (Bell et al. 1994) and FUV to UV spectroscopy (Prinja et al. 2007; Patriarchi & Perinotto 1997). The widespread and rapid line profile variation present in our *HST*/STIS time-series is demonstrated in Fig. 1 which shows

ratios of the individual STIS spectra divided by the mean for the time-series as a dynamic spectrum (i.e. a two-dimensional image of the time ordered ratios).

The temporal behaviour seen in Fig. 1 is remarkable. In addition to the ‘classic’ blueward migrating and recurring discrete absorption components (DACs) present in the unsaturated resonance line doublet of SiIV $\lambda\lambda 1394, 1403$ and in the subordinate excited state lines of OIV $\lambda\lambda 1339, 1344$ and OV $\lambda 1371$, the numerous FeVI absorption features between $\sim \lambda\lambda 1260$ to 1310 \AA and FeV lines between $\lambda\lambda 1390$ to 1460 \AA also vary *in concert* with the wind lines. Three DAC episodes are evident over ~ 5.8 hr (see also Fig. 2): There is some empirical resemblance in optical depth and velocity dispersion between the first episode ($T \sim 0.3$ to 2 hr) and the third feature ($T \sim 3.7$ to 5.5 hr). The second DAC episode ($T \sim 2.3$ to 3.3 hr) is weaker though it has a similar blueward velocity progression. We note that the individual spectra were normalized to suppress an overall continuum variability of $\sim \pm 4\%$, which is similar in amplitude and time scale to that seen in the optical by Bell et al. (1994). Because the time dependence is not obviously in phase with the DACs, its exact origin is not clear. However, the wavelength independence of the continuum variability suggests that it results from some sort of geometric obscuration instead of temperature irregularities.

The reaction of the deep-seated Fe lines indicates that the wind structures originate very close to or at the stellar surface. The variations in excited lines of OIV and OV provide further strong support of this deep-seated origin. In general, a stellar flow need not be a monotonically increasing function of distance from the star and an absorption feature seen at low velocity in a resonance line need not originate close to the star (e.g., Owocki et al. 1988). In contrast, in dense expanding winds the populations of the excited levels require a strong EUV radiation field, thus these transitions have a strong dependence on the radial distance from the star. This means that large populations of the lower levels of OIV and OV ions can only occur close to the star. We conclude therefore that the evolving features seen in Fig. 1 in the fast wind NGC 6543 originate at the stellar surface.

The short time-scale fluctuations in the numerous Fe ‘forest’ lines also imply that the surface conditions on the CSPN are non-uniform, and likely to affect the results of 1-D model atmosphere analysis. This may account for the inconsistencies Georgiev et al. (2008) report in their non-LTE analysis of HD 164963, including an overabundance of Si, observed spectral features not present in the model, differing wind velocities for different resonance lines, and the need for additional ionization sources in the external part of the fast wind.

4. CO-ROTATING INTERACTION REGIONS

The variability patterns observed in OIV, OV and HeII $\lambda 1641$ are shown in closer (velocity) detail in Fig. 2, where some further characteristics are revealed. Firstly, the line profile modulations tend to be bow-shaped in the direction of increasing time, i.e., an absorption enhancement occurs first at an intermediate velocity and then spreads to higher (bluer) and lower (redward) velocities simultaneously at a later time. This ‘phase bowing’ is particularly evident in the dynamic spectra of OIV and HeII. Similar forms of variability have been identified in the stellar winds of OB stars (e.g., Fullerton et al. 1997; de Jong et al. 2001; Prinja et al. 2002). Hydrodynamic models by Cranmer & Owocki (1996) (see also Lobel & Blomme 2008) showed that large scale, pro-azimuthal, wind structure in the form of co-rotating in-

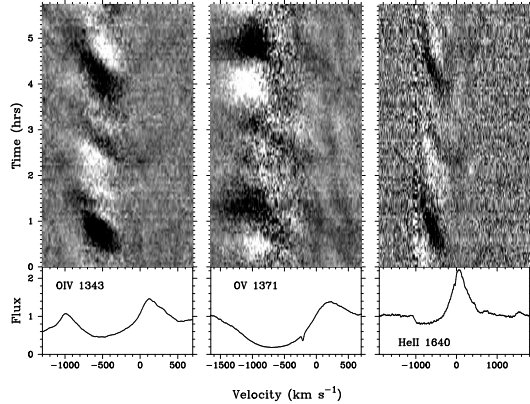


FIG. 2.— Dynamic spectra of OIV, OV and HeII revealing bow-shaped modulation that extends blueward and redward simultaneously in time. Note also the ionization shift between OV and the lower ions OIV and HeII.

teraction regions (CIRs) can explain the characteristics of the bowed discrete absorption components. The CIR structures are akin to those seen in the solar wind (e.g., Hundhausen 1972; Mullan 1984), where different sectors of the stellar surface give rise to winds which accelerate differently. When, due to rotation, these different sectorial flows interact, an interface with a spiral pattern results and a velocity plateau develops along the interface. As the CIR pattern rotates across our line of sight to the stellar disk, it creates an absorption in the dynamic spectrum which evolves toward high velocity. Intensity irregularities at the stellar surface, such as spots, non-radial pulsations, or granulation can potentially alter the radiative wind acceleration locally, thus giving rise to streams of faster and slower material, which interact to form the CIRs.

We also note in Fig. 2 evidence for an ionization shift, where the absorption enhancements with respect to the mean profile (i.e. darker patches) in OV lag those in the OIV and HeII by about 1 hr. (See, e.g., the episode between $\Delta T \sim 4$ and 5-hr in Fig. 2). This may be evidence for an ionization gradient across the CIR, with the lower ions on the leading edge of the CIR and higher ions on the trailing edge.

5. CONSTRAINING THE STELLAR ROTATION RATE

We have demonstrated that the UV wind lines of NGC 6543 are extensively variable, and that the variability results from large-scale, coherent wind structure. The characteristics of the variability, including bow-shaped modulations, are consistent with co-rotating interaction regions (CIRs) that are rooted at the stellar surface. In this section we use the temporal evolution of the DACs to constrain the rotation rate of the central star in NGC 6543.

By their very nature, CIRs infer rotation. They have been detected in the winds of O (Kaper et al. 1997; de Jong et al. 2001) B (Fullerton et al. 1997; Prinja et al. 2002) and WR stars (e.g., Chené & St-Louis 2011). Typically, the signatures of 2 strong CIRs are seen, but these are sometimes accompanied by two weaker arms (Fullerton et al. 1997, de Jong et al. 2001). It seems reasonable, therefore, to associate the two strong features which occur at $\Delta t \simeq 0.3$ and 3.7 hours in Figures 1 & 2 as strong CIRs and the one near 2.3 hours as a weaker one. Thus, we estimate the rotation period of HD 164963 is $2 \times (3.7 - 0.3) \sim 6.8$ hours. In this case, its rotation rate is $\simeq 179R \text{ km s}^{-1}$, where R is the stellar radius in solar units. The most recent line-blanketed non-LTE line synthesis analysis of the central star yields estimates of R for

HD 164963 that vary between 0.3 (Table 1) and 0.6 (Herald and Bianchi 2011). We therefore estimate its rotation rate to be in the range $54 \leq v_{\text{rot}} \leq 108 \text{ km s}^{-1}$.

6. DISCUSSION

State-of-the-art stellar evolution calculations of rotating, single low-mass stars predict a substantial spin-down during their late phases of evolution. This is because, despite a possibly high initial rotation rate, the dramatic expansion and increased mass-loss during the RGB and AGB phases result in huge angular momentum loss. Coupling between the core and the envelope is provided by angular momentum transport processes, arising from rotational instabilities and magnetic torques. This coupling is required to explain the slow rotation rate of white dwarfs and, for more massive progenitors, neutron stars (Heger et al. 2005; Suijs et al. 2008). Moreover an angular momentum transport in radiative zones like the one provided by magnetic torques is necessary to reproduce the near uniformity of the solar rotation profile (e.g., Eggenberger et al. 2005) and possibly the recent asteroseismic observations of the red giant KIC 8366239 (Beck et al. 2012; Eggenberger et al. 2012). However we want to stress that the angular momentum transport produced by magnetic torques relies on the existence of a dynamo in the radiative layers of stars (Tayler-Spruit dynamo, Spruit 2002), which is currently debated (e.g., Zahn et al. 2007). Other angular momentum transport processes in radiative zones have also been proposed (e.g., gravity waves Talon & Charbonnel 2005).

We have used the Modules for Stellar Experiments in Astrophysics (Mesa version 4298 Paxton et al. 2011) code to calculate the evolution of a grid of low-mass stars ($1.5M_{\odot}$, $2M_{\odot}$ and $3M_{\odot}$) with metallicity $Z = 0.02$ and initial equatorial rotational velocity of 250 km s^{-1} . This code accounts for the transport of angular momentum by rotational instabilities and magnetic torques (see e.g., Heger et al. 2000, 2005; Suijs et al. 2008). We adopted the mass-loss rate of Reimers (1975) during the RGB evolution and the one of Bloeker (1995) during the AGB and post-AGB phase. Our $1.5M_{\odot}$ model provides the best fit to the values of luminosity ($1585L_{\odot}$) and effective temperature (67000K) determined by Georgiev et al. (2008), however the major results discussed below do not change for the other calculations. We find that when the star reaches the CSPN phase, it has lost most of its angular momentum and its surface rotation velocity is much lower than 1 km s^{-1} (see Fig. 3). Therefore calculations that adopt the physical ingredients required to explain both progenitor and descendant stars of CSPN, are at odds with the limits on the rotation rate of NGC 6543 derived in Sect. 5. Note that DACs seem to be frequent among CSPN (Prinja et al. 2012). Since to be observable DACs usually need to recur on a short period, this suggests that rapid rotation could be widespread among CSPN (where here rapid means rotating faster than the predictions of single stellar evolution calculations).

An interesting possibility is that NGC 6543 did not evolve as a single star. In a binary system spin-up of one or both components could result from mass accretion, tidal interaction or a merger. This is particularly interesting in the case of CSPN, as binarity has been often discussed as a possible explanation for the asymmetric shapes of PNe (see e.g., Iben 1995; Balick & Frank 2002; Huarte-Espinosa et al. 2012).

CSPN are hot and luminous, and due to an iron opacity peak at about 150000 K , they can develop a subsurface convection region. This occupies a negligible fraction of the stellar mass, but at the same time occurs very close to the stellar surface.

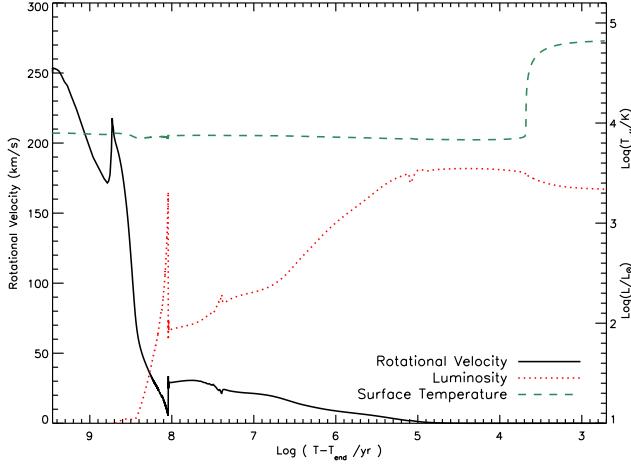


FIG. 3.— Evolution of the equatorial rotational velocity for our $1.5M_{\odot}$ model with metallicity $Z = 0.02$ and initial equatorial rotational velocity of 250 km s^{-1} . The horizontal log scale shows the time to the end of the calculation, when the luminosity and surface temperature roughly correspond to the estimated values for the central star of NGC 6543 (See Table 1). The model includes angular momentum transport induced by rotational instabilities and magnetic torques. The evolution of stellar luminosity (dotted line) and surface temperature (dashed line) are also shown for reference.

Our model of the central star of NGC 6543 reveals the presence of such convective layer, with convective velocities of about 10 km s^{-1} ($\sim 15\%$ of the local sound speed; CSPN models with higher initial mass result in higher velocities). Note that the presence of this convective layer is a robust result. It is a structural property depending only on the opacity and luminosity, and therefore we do not expect major changes if the star went through binary interactions. Like the case of

massive OB stars, it is possible that such convection zones can produce density and velocity fluctuations at the surface, stochastically excite oscillations and produce magnetic fields (Cantiello et al. 2009; Cantiello & Braithwaite 2011). Interestingly the recent observation of stochastic brightness variations in the CSPN of NGC 6826 (Jevtić et al. 2012) could be related to the presence of such subsurface convective layers. The non-uniform surface conditions revealed by the Fe V and Fe VI line profile variability in NGC 6543 seem to further support this notion. If a dynamo¹ is at work in the iron convection zone of NGC 6543, adopting the densities and MLT convection velocities from our models one finds an equipartition field $B \sim 2\text{ kG}$ (inside the convective region). Similar to the case of massive OB stars discussed in Cantiello & Braithwaite (2011), these fields can in principle reach the stellar surface through magnetic buoyancy and affect the stellar surface (e.g. creating bright spots). Bright spots have been discussed as a way to produce CIRs (Cranmer & Owocki 1996), which might provide an explanation for the common emergence of DACs in CSPN (Prinja et al. 2007, 2012).

Our work shows that observations of DACs in CSPN can provide important constraints on the surface rotational velocity of these intriguing stars. In turn this information can be used to constrain their evolutionary history, potentially shedding light on the puzzling origin and shaping of planetary nebulae.

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¹ The convective turnover timescale is of order hours, comparable to the inferred rotational period of NGC 6543. This means that the Rossby number

is of order unity and that an $\alpha\omega$ -dynamo might be at work.